Package Accession Number ML010520307

February 20, 2001

MEMORANDUM TO: William F. Kane, Director
Office of Nuclear Material Safety and Safeguards

FROM: Ashok C. Thadani, Director **/RA/**
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER RIL-178, "BURNUP CREDIT FOR TRANSPORT AND DRY CASK STORAGE OF PWR SPENT NUCLEAR FUEL"

This research information letter (RIL) provides the technical bases for our recommendations to increase the applicability of burnup credit (BUC) to transport and dry cask storage of spent nuclear fuel (SNF) from pressurized water reactors (PWRs). Although the Spent Fuel Project Office (SFPO) Interim Staff Guidance 8, Rev. 1 (ISG8R1) provides increased flexibility in the guidance for licensing of spent nuclear fuel (SNF) casks, with some modifications, it can be made applicable to cover a greater population of present and future SNF. The issues within the ISG8R1 that are candidates for modification are: (1) spent fuel cooling time; (2) burnable absorbers in spent fuel; (3) axial burnup profiles; and (4) fuel loading offset as a function of initial enrichment.

Executive Summary

This RIL provides a summary of the technical bases for our recommendations to increase the applicability of BUC to transport and dry cask storage of SNF from PWRs. The Office of Nuclear Regulatory Research (RES) recommends revising ISG8R1 to: (1) relax the assumed 5-year allowed SNF cooling time condition; (2) allow BUC for assemblies that have used burnable absorbers (both burnable poison rods as well as integral burnable absorbers); (3) endorse the adequacy of existing Yankee Atomic axial burnup profile database for obtaining profiles for the use with actinide-only burnup credit, pending completion and review of a report on this subject, as described in Reference 1; and (4) remove the loading offset penalty. The RIL also discusses ongoing research on criticality safety code validation and development of a technical basis for full BUC, as well as assessment of experiment and measurement technologies for BUC. Reference 1 is provided with this RIL.

Background

The regulations for transport and dry storage of SNF are promulgated in 10 CFR Parts 71 and 72, respectively. Current industry practice is to design spent fuel canisters that can be inserted into either dry storage or transport cask designs, thus eliminating the need for further handling of spent fuel assemblies once they have been loaded in a canister at the facility. The transport regulations of Part 71 provide the limiting condition for criticality safety, including consideration of water in-leakage to the canister. Although neither Part 71 nor Part 72 has any specific requirement that would prevent BUC from being implemented in the safety analysis, the historical practice for criticality safety analyses for transport and dry cask storage has been to assume the SNF is unirradiated, with uniform isotopic compositions, corresponding to its maximum initial "fresh fuel" enrichment of ^{235}U. This fresh fuel assumption provides a well-defined, straightforward, and bounding approach that eliminates the need for information on the irradiation (reactor operating) conditions and reactor power history. However, while being bounding, the fresh fuel assumption inherently leads to overly conservative cask designs. Improved realism allowed with BUC enables increases in cask capacity for a given package volume and/or allows loading of SNF with higher initial enrichment values.

Because there hasn't been a licensing application using BUC to date, there has been no regulatory experience in the U.S. with licensing of a PWR or boiling water reactor (BWR) transport cask. France is the only country that has licensed the use of BUC in transport, having over a decade of experience with limited BUC and a significant experimental program to support expansion of BUC beyond current restrictions. In the same timeframe, the U.S. industry and the U.S. Department of Energy (DOE) supported a significant number of technical investigations, focused primarily on PWR fuel, to provide a foundation for implementation of BUC in this country. Based on this information the SFPO issued Interim Staff Guidance 8 (ISG8), entitled *Limited Burnup Credit,* in May 1999. Supported by initial confirmatory research from RES, Revision 1 to ISG8 (ISG8R1), entitled *Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks,* was released in late July 1999. ISG8R1 provides increased flexibility in the guidance for licensing of SNF casks. BUC uses the nuclide inventory (or an appropriate subset) for the irradiated fuel composition, instead of the fresh fuel nuclide inventory, and so consequently provides a lower, more realistic estimate of the effective neutron multiplication factor (k_{eff}) for the cask. Thus, while designing to the same margin of subcriticality, the improved realism allowed with BUC enables increases in cask capacity for a given package volume and/or allows loading of SNF with higher initial enrichment values.

ISG8R1 provides specific recommendations for licensees and the U.S. Nuclear Regulatory Commission (NRC) staff to consider in the preparation and review of the criticality safety analysis for a PWR cask using BUC. Some of these recommendations restrict the amount of reactivity credit that can be used in the safety assessment (e.g., credit for fission products is not allowed) and some restrict the SNF population (type and range of characteristics) that would be allowed in a BUC cask. These recommendations were based on: 1) technical information available to NRC at the time ISG8R1 was issued; 2) consistency with the industry standards developed for criticality safety of fissionable material (ANSI/ANS-8.1) and light-water reactor (LWR) fuel (ANSI/ANS-8.17) in operations outside reactors; and 3) recognition that experience and additional research being supplied by RES will provide a basis for additional guidance.

Current industry licensees have indicated to NRC that issuance of ISG8R1 has provided the impetus to prepare a new generation of high-capacity cask designs using BUC in the safety evaluations and a preliminary cask design using BUC has been recently presented (Ref. 2). However, adherence to the recommendations of ISG8R1 unnecessarily limits the population of SNF that can reside in a BUC cask, and restrict the use of BUC casks for fuel with high initial enrichment values. Therefore, RES has initiated a research program to clarify guidance on acceptable technical approaches, to develop approaches for expanding the range of BUC, and to address regulatory needs for safe, simple, and cost-effective implementation of BUC.

Since the implementation of BUC is an international activity, input and experience from domestic and international experts and organizations hava been, and are being, sought and incorporated into the RES program. A useful tool for this input is an expert panel convened to participate in a process of developing Phenomena Identification and Ranking Tables (PIRT). RES programs have used "PIRT" panels to provide input and information on a number of technical issues arising during the past few years. The PIRT panel for BUC consists of 16 experts: seven international participants from countries with significant interest and experience working on BUC issues, and nine participants representing a variety of domestic organizations and areas of expertise. The main goal of the PIRT panel is to identify phenomena, parameters, procedures, etc., that influence the determination of the neutron multiplication constant (k_{eff}) for spent fuel in a cask environment, provide a graded (e.g., high-importance, moderate-importance, or low-importance) ranking of the phenomena and, as appropriate, judge the uncertainty associated with each phenomenon. Besides its primary objective, the PIRT process can also facilitate a beneficial exchange of information and ideas that leads to improved understanding of the issues and practical approaches for effective implementation of BUC within the licensing process. The activities of the PIRT panel have been placed on an NRC web site at www.nrc.gov/RES/pirt/BUC/index.html.

Discussion

The development of technical bases, proposed recommendations for near-term technical closure for selected issues within ISG8R1, review of the progress made to date, and future plans for other BUC-related activities are discussed in this section.

A. Development of Technical Bases and Near-Term Technical Closure for Selected Issues within ISG8R1

Although ISG8R1 allows for the use of BUC in cask licensing applications, it has a number of limiting assumptions. The RES program has focused on eliminating these limiting assumptions and recommending closure in four technical areas: 1) spent fuel cooling time; 2) burnable absorbers in spent fuel; 3) axial burnup profiles; and 4) fuel loading offset as a function of initial enrichment. Each of these limiting assumptions were included in ISG8R1 because of a lack of information and/or technical confirmation of the characteristic behavior relative to SNF transport and storage. The issues surrounding each technical area are briefly discussed below and a summary of the recommendations developed to address each technical area is provided. It should be noted that these are recommendations for acceptable approaches, and are not intended to exclude other approaches.

B. Spent Fuel Cooling Time

A source of subcritical margin, inherent in the current NRC position of ISG8R1, is the assumption that only SNF cooled greater than 5-years be loaded in the cask and a fixed 5 year cooling time be used in the safety analysis. It has been established that longer cooling times will decrease the reactivity until the 100- to 200-year timeframe (dependent on cask conditions and assumptions) when reactivity will subsequently increase (but not above the level established at 5 years). RES investigations have been performed to quantitatively establish the reactivity behavior of SNF with cooling time from discharge to 100,000 years for a variety of cask conditions and analysis assumptions (Ref. 1). These investigations have demonstrated that safety analyses assuming cooling times up to 40 years would allow additional negative reactivity credit and maintain a consistent margin of subcriticality assuming the SNF is removed from the cask before a 200-year cooling time, which may be considered a practical lifetime for dry storage and transport casks. Therefore, RES recommends revising ISG8R1 to relax the assumed 5-year allowed SNF cooling time condition.

2. Inclusion of Burnable Absorbers in Spent Fuel

As the conservatisms in BUC analyses are better understood and reduced, the population of SNF acceptable for loading in a cask will be increased. At the present time, ISG8R1 only addresses PWR SNF that has not contained burnable absorbers. Burnable absorbers, such as burnable poison rods (BPR), integral fixed absorber rods, and axial power shaping rods are all in common use in PWR fuel designs. The hardened spectrum resulting from the presence of removable burnable absorbers (caused by the removal of thermal neutrons by capture and by the displacement of moderator) increases the reactivity of discharged SNF in comparison to similar SNF that was not exposed to burnable absorbers. For burnable absorbers that are an integral (non-removable) part of the fuel assembly, the reactivity effect may be either positive or negative, depending on the burnable absorber design (Ref. 1).

RES recommends that ISG8R1 be revised to include BUC for assemblies that have used burnable absorbers. The reports that have been documented within the RES program (Ref. 1) indicate several technically valid approaches, ranging from a bounding conservative approach to a more realistic approach, that applicants could use in their safety analysis report. It is anticipated that any approach selected by applicants would be dependent on: 1) the breadth of reactor operations and assembly design information available for the analysis; 2) the level of rigor to achieve realism in the analysis; and 3) the measures employed to assure loading integrity. For example, safety analyses for casks that are to be loaded with assemblies which contained burnable absorber rods during irradiation should account for the limiting realistic BPR irradiation justified by the applicant's operations and design information and/or verified during cask loading. The technical reports (Ref. 1) characterize the effect that burnable absorbers have on SNF reactivity and provide a means to confirm the adequacy of the assumptions and approaches used in the safety analysis.

3. Bounding Axial Burnup Profiles

In comparison to the present fresh fuel assumption, the use of BUC can significantly increase the complexity of the criticality safety analysis performed for a cask design. Such complexity is directly related to the need to consider the irradiation conditions and power history for the SNF. Since a cask is licensed for specified contents, the impact of the reactor operating history and conditions on the reactivity of the SNF under cask conditions must be considered in a realistically bounding manner. Currently, ISG8R1 recommends use of irradiation conditions and power history that provide a conservative estimate of k_{eff} for SNF under cask conditions.

To better understand the impact of this recommendation, work has been undertaken to assess processes for obtaining the realistic range of reactor conditions and history variations and subsequently evaluate this information in the context of a realistic risk-informed approach to the safety analysis. The goal is to provide clarifying guidance relative to a process that maintains adequate safety margin without imposing undue conservatism. For example, it is well-established that k_{eff} for SNF in a cask is very sensitive to the axial burnup profile resulting from reactor irradiation. Therefore, work has been undertaken to assess the existing database of axial profile information and propose guidance on the use of such a database, both within the context of ISG8R1 and with consideration of potential future modifications of ISG8R1.

Although the existing calculated axial profile database, which was derived from core physics codes and prepared by Yankee Atomic (YAEC-1937) is large, it is not exhaustive. One of the expressed concerns has been the adequacy of this finite database to completely represent the variety of possible profiles resulting from irradiation in U.S. PWRs, particularly as the initial enrichments and burnup increase. To address this concern, RES has supported a statistical evaluation of the neutron multiplication factors resulting from the axial burnup profiles within the current database, to assess the likelihood of the existence of significantly more reactive axial burnup profiles and the associated consequences to the neutron multiplication. This evaluation has demonstrated that bounding profiles derived from the current database are statistical outliers that yield notably higher estimates of the cask k_{eff} than the typical or mean profiles. Thus, the probability of the existence of SNF assemblies with significantly more reactive axial burnup profiles is very low.

Therefore, RES recommends endorsement of the adequacy of the existing Yankee Atomic axial burnup profile database for obtaining profiles to use for actinide-only BUC for PWR fuel pending the full study indicated in Ref. 1 has been received and reviewed by RES. As noted previously, the technical reports that have been documented for the RES program (Ref. 1) indicate that the profiles derived from this database represent statistical outliers which are a good source in the search for bounding profiles to use in the BUC calculations. In some cases, additional data may be necessary to show that a particular profile is sufficiently bounding. Also, applicants seeking to use more realistic profiles may need to expand the database and/or provide measurement verification of the assembly burnup profile selected for cask loading. RES is currently working to investigate the benefits and risks involved in risk-informed approaches that enable use of more realistic (less bounding) profiles without measurement verification.

4. Loading Offset as a Function of Fuel Enrichment

The paucity of post-irradiation isotopic assay data and the large uncertainties typically associated with fission product cross-sections were the major factors in NRC's decision to address only actinide compositions associated with burnup values up to 40 GWd/MTU, in its current version of its burnup credit guidance (ISG8R1). In addition, although fuel with initial enrichments up to 5.0 wt percent is included, there is an offset penalty for initial enrichments over 4.0 wt percent such that, for every 0.1 wt percent enrichment above 4.0 wt percent, the loaded assembly should have a burnup value 1 GWd/MTU above the burnup value used in the safety evaluation. Studies indicate that the current bounds of the guidance will not limit the design of BUC casks and will allow a significant population of the SNF currently in pool storage to be moved to dry cask storage and/or transported. However, expansion of the scope of the guidance such as: 1) inclusion of the negative reactivity provided by fission products in SNF; 2) removal of the enrichment offset; and 3) inclusion of burnup above 40 GWd/MTU in the BUC guidance will be needed to allow much of the remaining and future spent fuel population to be moved to dry cask storage and/or transported. The RES program has completed an assessment of the impact of the penalty, in terms of excess reactivity margin, associated with the loading offset, and has determined the technical criteria that would justify its modification or removal. Preliminary sensitivity analyses indicate that the sensitivities change very little with increasing enrichment within the 4 to 5 wt percent enrichment range. Similar efforts to develop the technical basis requirements for credit of fission product nuclides and extended burnup beyond 40 Gwd/MTU have been initiated. As new experimental data become available and/or existing experimental data are evaluated, an improved understanding of the current subcritical margin available in these conservative assumptions will be obtained and the potential for increased BUC can be realized.

RES recommends that ISG8R1 be revised to eliminate the loading offset penalty. As provided in Ref. 1, the bases for these recommendations, in particular, are: (1) the negative reactivity margin associated with fission products will more than offset any additional isotopic uncertainties caused by increased enrichment; (2) preliminary sensitivity analyses indicate that the sensitivities change very little with increasing enrichment (within this range); and (3) limited isotopic data will soon be available in the range of 4.0-4.65 wt percent to help quantify the uncertainties.

B. Progress and Plans for Other BUC-Related Activities

Progress and plans for other BUC-related activities are discussed in this section and include: (1) criticality safety code validation for BUC applications; (2) development of a technical basis for extension of regulatory guidance to include full BUC for PWRs as well as BWRs, and mixed-oxide (MOX) fuel and, (3) assessment of experiment and measurement technologies for BUC.

1. Criticality Safety Code Validation for BUC Applications

Although the criticality safety codes used in the analysis of transport and dry cask storage of nuclear fuel have been extensively validated under the fresh fuel assumption, there has been less code validation using irradiated fuel. Therefore, part of the RES program is devoted to extending the code validations for increasing burnup. For operations with fissile material outside reactors, NRC has endorsed the ANSI/ANS-8.1 standard as the basis for proper validation of computational methods in criticality safety analyses. This standard calls for validation of the methods using comparison with measured experimental data demonstrated to be applicable to the system being analyzed. Thus, application of ANSI/ANS-8.1 to validation of analysis methods used in BUC creates additional challenges because both the depletion and criticality analysis methodologies need to be considered and because no spent fuel critical experiments have been performed in cask geometries. The nature of experimental data appropriate for use in validation of BUC methodologies, and the value and applicability of such data have been debated topics for over a decade. Experimental data that have been considered in this country and others (France, United Kingdom, and Japan) include: chemical assays of SNF inventories; critical experiments performed with unirradiated uranium-oxide and MOX fuel in cask-like geometries; reactor critical configurations from power reactor restart measurements; subcritical experiments; and reactivity-worth experiments. Validation approaches that provide the bias and uncertainty associated with criticality analysis methods have traditionally relied solely on comparison with critical experiments. Inclusion of other types of experiments has required and will continue to require consideration of validation approaches that provide an effective means to combine the calculated-to-measured correlations from the different types of experiments.

The RES program has identified and reviewed potential sources of experimental data (domestic and international) (Ref. 3), and assessed the relative applicability of the data using sensitivity and uncertainty analysis (S/U) techniques developed under previous RES programs (Ref. 4). The S/U techniques are rigorous, physics-based approaches that are also being investigated as a means to help reduce the quantity of experimental data required to provide reliable estimates of the bias and uncertainty of analysis methods. As needed, the RES program is seeking access to existing experimental data and/or involvement in experimental programs judged of importance to an improved understanding of the physics and validation of analysis methods used to support licensing. Validation approaches for combining the bias and uncertainty derived from the different types of experiments are being investigated to assess their potential for incorporating additional information that may support improved confidence in subcritical limits.

2. Development of a Technical Basis for Extension of Regulatory Guidance to Include Full BUC for PWR, as well as BWR and MOX

Unirradiated BWR fuel assemblies have comparably less reactivity than unirradiated PWR fuel and the criticality safety controls needed for increased cask capacities have historically been obtained using neutron absorbers within the cask basket materials, compared to flux traps, as used in PWR casks. Thus, although the need for BUC for BWR fuel has been less than that for PWR fuel, it appears that use of limited BUC may be needed to enable cask loading of BWR fuel with average initial enrichments near 5.0 wt perecent. Hence, a longer-term objective of the RES program is to assess the BUC technical issues discussed above as they relate to BWR SNF and determine the need for developing the technical basis for such a position. The current DOE program for irradiating MOX fuel in commercial reactors may also generate a need for establishing a technical basis for dry storage and transport of MOX fuel, using BUC assumptions.

The RES work on BUC issues regarding transport and storage will benefit other technical areas of importance to NRC. For example, the criticality safety methodology proposed for licensing of the high-level waste repository seeks to use BUC for waste packages loaded with commercial PWR and BWR SNF. Thus, although implementation will vary based on the regulatory criteria for the repository, many of the technical issues discussed above are relevant to consideration of BUC in the repository. Similarly, the shift of the industry to high burnup fuel regimes and the commensurate need for dry cask storage and transport of such fuel has led to an identified need to better characterize such fuel and improve understanding of source terms (e.g., isotopics, decay heat, and radiation sources). The RES BUC activities to review, evaluate, and analyze post-irradiation chemical assay data, using both traditional and sensitivity and uncertainty techniques should provide an improved understanding of the uncertainties associated with high burnup source terms. Such an understanding will benefit the planned effort to extend Regulatory Guide 3.54, which recommends decay heat values for use in independent spent fuel storage facilities (e.g., dry casks).

3. Assessment of Experiment and Measurement Technologies for BUC

The current staff position is that, before or during the loading of a BUC cask, a measurement should be performed to confirm the reactor record of the assembly burnup. The measurements described in ISG8R1 can be calibrated against reactor records and therefore will check the internal consistency of these records as well as provide some protection against misloadings. Specification for such a measurement is consistent with Regulatory Guide 3.71, the International Atomic Energy Agency regulations for transport of radioactive material, and current practice in France. Beyond confirming the reactor record, measurements of burnup that obtain the axial burnup profile for an assembly could facilitate the use of typical axial profiles in the safety analysis. Such use of typical profiles could eliminate the need for developing a bounding profile and reduce conservatism in the subcritical margin by 2-4 %Δk. However, the confidence that industry maintains in its reactor records, the potential increase in dose to workers that may result from measuring each assembly, and the cost of the pre-shipment measurement are all reasons to use a risk-informed process to further understand the potential consequences of eliminating the pre-shipment measurement and relying solely on reactor records to assure that the loaded SNF assemblies meet the criteria specified by the safety analysis. In addition, RES will investigate alternative measurement approaches that might reduce worker dose and total loading cost while maintaining adequate assurance of SNF characteristics.

The potential use of subcritical measurements at the time of loading to provide an assessment of proper cask loading (i.e., ensure k_{eff} remains below a specified limit) is also a concept that may be explored as an alternative to burnup measurements (per ANSI/ANS-8.17) of each assembly. This concept would need extensive development in terms of technical advancement and practical implementation within casks designed for loading at a reactor site with borated water. However, when fully mature the process might provide an expedient resolution of many of the technical issues discussed above. For example, the use of subcritical measurements could potentially support the allowance of best-estimate criticality safety analyses to establish the licensing safety basis, and so substantially expand the allowable BUC and virtually eliminate SNF population restrictions by providing whole-cask qualification.

Summary

Much of the difficulty associated with implementing BUC has been in validating an approach that quantifies the reduced conservatism associated with BUC for the diverse population of SNF and the associated range of irradiation conditions, burnup values, initial enrichment values, and cooling times. RES has a program in place to perform research that has supported the near-term objectives of providing technical bases and regulatory guidance while identifying and evaluating potential pathways for resolution of technical issues that can improve understanding of safety margins and facilitate effective implementation of BUC for the full population of current PWR and BWR fuel designs. RES has provided the technical bases recommendations for the near-term closure of four selected issues within ISG8R1.

References:

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3. Phillip Fink and Temitope Taiwo, "Potential Sources of Experimental Validation for Burnup Credit," Argonne National Laboratory, ANL/TD/00-11, January 2000.

4. B.L.Broadhead, et al., "Sensitivity and Uncertainty Analyses Applied to Criticality Safety Validation," NUREG/CR-6655, November 1999.

5. Phillip Fink and Temitope Taiwo, "Potential Sources of Experimental Validation for Burnup Credit," Argonne National Laboratory, ANL/TD/00-11, January 2000.

6. B.L.Broadhead, et al., "Sensitivity and Uncertainty Analyses Applied to Criticality Safety Validation," NUREG/CR-6655, November 1999.

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3. Phillip Fink and Temitope Taiwo, “Potential Sources of Experimental Validation for Burnup Credit,” Argonne National Laboratory, ANL/TD/00-11, January 2000.

4. B.L.Broadhead, et al., “Sensitivity and Uncertainty Analyses Applied to Criticality Safety Validation,” NUREG/CR-6655, November 1999.

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